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Entropy, Environment and Endogenous Economic Growth[*]

by

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Abstract

This paper investigates the proper modeling of the interaction between economic growth and environmental problems, summarizes under which conditions unlimited economic growth with limited natural resources is feasible, and describes how sustainable growth can be achieved. It synthesizes the results from various environmental endogenous growth models.

The physical dimension and the value dimension of economic activity have to be treated as conceptually distinct. Accumulation of natural variables is bounded due to biophysical laws (notably, the entropy law). However, economic value may grow through the substitution of reproducible human inputs for natural inputs. The properties of knowledge, which is the primary human input, do not contradict unlimited new knowledge creation.

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Introduction

It seems that mainly current generations benefit from the way present Western economies are structured, growing and changing. Future generations may be worse off when unsustainable consumption levels and investment patterns translate (after possibly a long time lag) into severe environmental disruption and decline of material standards of living due to scarcity of resources. Unless the concern for the future generations is low, this may be suboptimal. From a moral point of view, unsustainable development conflicts with fairness to future generations. Hence, the challenge is to achieve sustainable development, defined as non-decreasing well-being for representative members of society over a long horizon (Pezzey 1992). This goal would be easier to attain if society would not have to abandon economic growth. It is true that on many occasions material growth and scientific progress have been criticized and accused of causing environmental and social problems (see e.g. Mishan 1993). However, mankind always tried, and often succeeded, to improve conditions of life by economic means (e.g. through establising agricultural production, trade or developing new industrial goods).

Is it possible simultaneously to realize economic growth and environmental preservation? Economics has attempted to address this question from different angles. The "mainsteam" literature focussed on exhaustible resources (e.g. Stiglitz 1974, Dasgupta and Heal 1974, Krautkraemer 1985). At the core were the importance of the price mechanism and the substitution possibilities of man-made inputs for natural resources. At the same time, others began to stress the economic implications of thermodynamic laws and ecology (e.g. Kneese, Ayres and d'Arge (1970), Daly (1973), Georgescu-Roegen (1971, 1975)). They insisted on the limits that physical and natural processes impose on economic activity and the difficulties in invoking the price mechanism because establishing property rights on environmental assets is often impossible. I will argue in this paper that these two views can complement each other and, more importantly, be reconciled by endogenous growth theory (initiated by Romer 1986). The central concept in this theory is the non-rival economic use of knowledge and its investment-driven creation. I propose a framework that synthesizes the neoclassical and ecological inspired approaches by taking knowledge and matter/energy as the primary inputs in the economic process. While matter and energy are subject to biophysical laws, knowledge use and knowledge creation are subject to their own peculiar regularities. As a consequence, it is the interaction between biophysical and social/psychologic/economic constraints that ultimately determines the feasibility of sustained growth in the creation of value in the economic process. Substitution of knowledge for matter enables an economy to derive more value from a given physical throughput in the economy. Sustainable growth, therefore, requires not only careful management of natural resources but also attention for knowledge creation.

The first part of the paper develops the concepts that are relevant in the discussion on economic growth and the environment. The criteria are provided for an appropriate incorporation of the environment in growth models. I argue that physical dimensions should be separated from economic value dimensions. Physical dimensions are bounded due to the laws of thermodynamics (conservation of energy/material and the entropy law). Section 2 presents and analyzes the basic structure of formal models that address environmental issues and economic growth. These models contain three building blocks: an ecological function, a production function and a preference function. The main links between the blocks are, first, the productive and amenity services that nature performs, second, pollution abatement activities and, third, the development of technologies (knowledge) that augment natural resource inputs. I explain under which type of specifications long-run growth is feasible. The final section summarizes implications for (the analysis of) public finance issues that can be derived within the proposed framework and points out some important areas for future research.

1. Concepts: how to reconcile unlimited growth with finite natural resources ?

Man has built his economy to deliberately raise the quality of life by the production and trade of goods and services. When the economic system contributes each period more to welfare by creating more value, economic growth arises. Economic value creation -- and hence economic growth -- is measured by calculating real market prices, which reflect the consumers' willingness to pay for marketed goods and services. An increase in the NNP figure indicates (if appropriately calculated) that the economy (as one particular means to affect our well-being) made positive direct contributions to welfare.[1] However, also activities outside the formal economy affect well-being so that GNP or NNP growth is not an index for overall well-being. NNP growth may be accompanied by deterioration in other fields so that, on average, welfare falls. This notion, of course, lies at the base of concern for crime, social disruption and environmental problems.

Environmental problems arise if the quality of the environment declines: if ecosystems are damaged, resources depleted, or species lost. As a consequence, the *physical* conditions for life deteriorate. Since economic activity depends on the environment (the environment is a source of resources to create economic value), economic growth and physical conditions of the environment interact. Economic activity may be the cause of environmental problems, but so might also a deterioration in physical conditions hamper economic processes.

In the analysis of the interaction between environmental problems and economic growth, ecological processes (for which *physical* magnitudes matter) have to be treated as conceptually distinct from economic processes (in which ultimately economic *value* matters). Both types of processes are subject to their own regularities. The ecological process is described by relying on biophysical laws, which deal with changes in physical states and conditions of biomass, material, and energy. Economic value creation represents the process in which human beings combine their ability and ingenuity with natural resources to produce desirable and marketable goods and services. Hence value creation is driven by technology and preferences -- which can both be viewed as the result of the human state of knowledge.[2]

1.1. Biophysical laws

The natural environment is limited in a physical sense. We observe no continuing rise in the physical quality of the air or the earth crust. Earth is basically a closed system with respect to material (except for the meteorites, which import material resources to the earth, and our activities in space that export material). No material can be created nor destroyed.

Georgescu-Roegen (1971) introduces the laws of thermodynamics to economics. According to the first law of thermodynamics (law of material/energy conservation), material is neither lost nor created in production processes or any other transformation process. According to the second law of thermodynamics (law of entropy), the transformation and rearrangement of material or energy inevitably implies an irreversible process from free or available energy into bound or unavailable energy. Material becomes irrevocably scattered (or dissipated), and hence less available. Transformation implies rising *entropy*, which can be seen as an index of the amount of unavailable energy in a given thermodynamic system at a given moment of its evolution (Georgescu-Roegen 1975, p. 351). The use of low-entropy energy in production inevitably yields high entropy energy as output (including wastes). All kinds of energy are gradually transformed into heat and heat becomes so dissipated in the end that man can no longer use it (Georgescu-Roegen 1975, p. 352). We cannot use the same amount of energy or material over and over again, because use or transformation is an entropic process. If in a closed system transformation implies dissipation of material, reassembling the dispersed material requires additional energy from outside. Disordered material requires more energy for processing (Daly 1992, p.93).

Fortunately, the earth is an *open* system with respect to energy. Every moment in time solar energy enters the system. The solar radiation provides the energy that compensates for the entropic processes on earth so that resources are renewable. Whereas natural and human transformation processes scatter available matter, new energy inflows provide the energy to recollect material and energy and to compensate for entropy. This explains the equilibrium in ecosystems and the renewable nature of natural resources. "The basic physical understanding of life is that it is an open system that imports low entropy from the environment and exports high entropy back to the environment, thereby maintaining its highly ordered structure in a quasi-steady state." (Daly 1992, p. 94). "[A] subsystem can maintain, even decrease, its entropy by sucking, as it were, free energy (alternatively, low entropy) from its environment" (Georgescu-Roegen 1971, p. 193).

However, the flow of solar energy that reaches the earth is fixed and beyond human control. Hence, the compensation for entropic processes is limited. The combination of the law of entropy and the existence of a bounded fixed energy inflow from outside implies that natural resources are scarce in an absolute sense (Daly 1987). The creation of useful low entropy natural resources is limited by this inflow. Within the entire history of the earth, we cannot use more than the low entropy resources that this inflow creates. Note that this applies to both what we call renewable resources and exhaustible resources: both are ultimately stocks of stored solar energy.

The notion of finiteness of natural resource creation has led to proposals to rely as much as possible on forms of energy and material that are efficient in the use of solar energy in order to enhance sustainability. We should refrain from expanding entropic processes and minimize entropic processes. The transformation of low entropy inputs into high entropy outputs should remain within the limits imposed by new energy inflows, such that a (quasi-)steady state with regard to physical flows and stocks can be sustained. A similar situation is defined in Daly's (1974/1980/1993) steady-state economy, where physical wealth and population are kept constant (Daly 1993, p. 29; cf. Perrings 1987).

1.2. The economic dimension

Although physical laws should be used to account for environmental problems, *physical* laws cannot be used to explain *economic* growth. Although economic activity (and production in particular) has an important physical dimension (volume, mass, or quantities of goods), it encompasses more than the transformation of free energy into bound energy, and also more than merely rearranging matter, which is inevitably entropic. We should not neglect that production is *economic* if it transforms low-value inputs into high-value outputs. Indeed, Georgescu-Roegen acknowledged:

> (...) the true "output" of the economic process is not a physical outflow of waste, but the *enjoyment of life*. (...) Without recognizing this fact and without introducing the concept of enjoyment of life into our analytical armamentarium we are not in the economic world. Nor can we discover the real source of economic value (...). [Georgescu-Roegen, 1971, p. 282]

While the ecological sphere determines physical states and conditions, the economic sphere deals with value, i.e. contributions to the enjoyment of life. Hence, an indicator of economic performance measures economic value rather than physical quantities. Economic growth is thus by no means necessarily bounded, although growth measured in physical quantities is. Or, as Daly (1993, p. 17) puts it:[3]

> (...) value could conceivably grow forever, but the physical mass in which value inheres must conform to a steady state, and the constraints of physical constancy on value growth (...) must be respected.

Although being restricted by physical constraints, economic growth can be realized by creating more value from the same amount of (low entropy) material and energy.

The system within which economic activity takes place can be represented as the interaction between the natural and the human sphere, where each sphere provides particular inputs and generates particular outputs. Boulding (1966) distinguishes between information, matter, and energy as the three important classes of inputs and outputs in a system. Obviously, material and energy are the specific inputs and outputs of the natural system, while information, or knowledge (to use the term that is common in the endogenous growth literature), is provided by the human sphere. Inter-human activity contributes to the system by providing knowledge; matter or energy, in contrast, are not man-made.

insert *Figure 1* Conceptual framework

The economic process combines human inputs (knowledge) and natural inputs (matter/energy) to produce economic goods. Both types of inputs are necessary. Imagine an economy with only natural inputs but lacking the knowledge about how to use them. Such an economy would not produce any economic goods. If an economy would have access to knowledge only but not to material or energy, knowledge could not be applied: it would be useless. The combination of knowledge and material/energy yields new inputs/outputs such as physical capital (which is knowledge frozen in material), labor (which is knowledge tied to (human) energy), extracted and processed natural resources (e.g. iron ore and steel), final consumption goods, etc.[4] The size and composition of the stock of knowledge determines how productive natural resources will be in creating economic value.

Figure 1 illustrates this conceptual framework. The economic process contains technology and preferences. The technology set describes how combinations of physical inputs and knowledge yield goods and services with certain characteristics. Preferences are formulated over these characteristics, since it is not the physical quantities that determine utility but the enjoyment derived from the goods.

Entropic processes and economic processes differ fundamentally. Entropy and economic value have no one-to-one correspondence. Many low-entropy types of energy and material are useless from an economic point of view because mankind lacks the knowledge how to use them productively. When new knowledge becomes available, the productivity of the economy increases without necessarily changing physical conditions (think of the improvement of the user manual for a complicated consumer product). In a physical sense, entropic processes degradate energy by turning concentrated (ordered) energy into dissipated (disordered) energy. However, the state of knowledge determines energy available for satisfying economic wants.

1.3. Knowledge creation

Now it has been established that physical and value dimensions matter for economic processes, the attention will turn to *economic growth*. One form of economic growth involves using more and more natural inputs while the knowledge about the productive use of these inputs does not progress. This "more-of-the-same" manner of growth inevitably hits the limits of resource exhaustion and availability of durable energy types due to the entropy law. In particular, diminishing returns set in because a faster rate of rearranging matter according to known procedures requires more and more energy, which is ultimately a fixed factor.

A second type of growth involves an increase in knowledge how to derive more productivity and utility from a given flow of material/energy. The associated technological progress makes feasible unlimited economic growth without deteriorating physical environmental conditions. For example, we prefer having a small light gadget (e.g. a television set) that is more "sophisticated" than having a large heavy "old-fashioned" gadget. By developing and employing new knowledge, we can at the same time reduce the material requirements of economic goods and increase the use value. New technologies may also enhance the productivity of waste products, e.g. by finding useful destinations for products that were previously considered only waste. Hence, new knowledge may lower the economically measured degree of "boundness" or unavailability of energy/matter. Finally, new knowledge may turn previously unusable natural goods into valuable economic goods (cf. Young 1991).

Whether unlimited economic growth may be feasible, therefore, depends on the "laws" applying to the accumulation of knowledge. Growth theory has recently reconsidered the concept of knowledge and the nature of knowledge creation. In particular, the pioneer of the endogenous growth literature Paul Romer (e.g. 1990a, 1990b, 1994) bases his analyses on careful conceptual considerations involving knowledge. According to Romer, a fundamental characteristic of knowledge is its *non-rival* nature. Once invented, an idea can be applied by many individuals in many places at many times without being worn out or suffering from congestion. Hence, a law of entropy does not apply to the diffusion of knowledge.

The use of ideas does not transform and degradate the total knowledge stock but is likely to add to this stock.[5] This contrasts sharply with the physical law of entropy. Knowledge breeds knowledge. New ideas are inspired by older ideas. The more one and the same idea is applied by others, the more likely it yields new insights. Old knowledge creates new knowledge and knowledge creates knowledge to create knowledge (cf. Stiglitz 1987). Although we never know for sure (since we are by definition talking about unknown things -- which new knowledge is), human creativity is not likely to be bounded.

However, new knowledge does not come free. In most instances, the creation of knowledge requires effort and takes time. In most cases, costs have to be incurred before the benefits arise. Invention and innovation are thus acts of investment. Within the conceptual framework visualized in Figure 1 the cost of knowledge creation has inevitably a physical dimension (like all economic goods), to be measured in natural inputs. The costs associated with the *use* of knowledge as an input are zero because knowledge is a non-rival input. Knowledge *creation*, in contrast, requires rival inputs. Consequently, knowledge creation interferes with entropy processes.

Knowledge creation is, at least to a certain extent, part of the economic process and hence sensitive to economic incentives. Firms may intentionally search for and develop new technologies and products. Commercial research and development add to the stock of knowledge. In other situations, new technologies are a side-product of economic activity through learning-by-doing.

1.4. Sustainable growth

Table 1 summarizes the discussion so far. We can now put together the different concepts to formulate a view on sustainable growth that is consistent with the requirements summarized in the table. The resulting framework synthesizes insights from three important approaches. First, the biophysical laws reveal that ultimately a sustainable economy is in a stationary state with respect to physical dimensions (Daly's steady state). Second, insights from endogenous growth theory show that the endogenous accumulation of knowledge may still contribute to growth (i.e. increase the value of marketable goods) within such an economy. Third, neoclassical principles demonstrate effects of prices, taxes and other incentives on resource use as well as the direction and speed of the accumulation of knowledge.

Table 1 criteria for modeling the interaction between growth and environment

a. environmental variables matter for their physical dimension;
b. the physical dimension of environmental processes is subject to the laws of thermodynamics, implying that -- because of the given inflow of external (solar) energy -- growth in natural resources is bounded;
c. economic growth matters in economic value terms;
d. both knowledge and natural inputs are essential in economic production;
e. without knowledge creation, economic growth runs into diminishing returns due to the laws of thermodynamics;
f. knowledge is man-made and in many respects non-rival;
g. knowledge creation requires investment (which in turn requires natural inputs);
h. knowledge creation need not be subject to diminishing returns.

Resource use and other physical aspects of the economy can be influenced by taxes on polluting private factors of production, energy and material inputs, etc. However, it may be difficult to exactly predict tax levels that result in constant physical dimensions, which is required for sustainability. Alternatively, issuing a fixed number of marketable resource extraction permits and pollution permits guarantees constancy in physical dimensions of the economy and preserves price incentives and the associated efficiency at the same time (Bovenberg and Smulders 1994). The resulting priced scarcity of natural resources stimulates private cleaning-up activities and the development of resource augmenting technology (Verdier 1993). New technologies that increase the average resource intensity of production are no longer profitable, so that technological progress will be biased in the direction that is necessary for sustainability. Imperfect patent protection, general knowledge spillovers, imitation, and the unintended nature of technology improvements that arise as a side-product of economic activity cause externalities in knowledge creation which may call for technology subsidies or public provision.

Technological progress may be slow and costly so that growth is not always sustainable. Neither is sustainable growth, if feasible, necessarily optimal. If time preference is high, future (environmental and economic) losses are easily compensated by high current (unsustainable) consumption levels. Society is then not willing to invest enough to guarantee non-declining consumption and environmental resources over time. Evidently, strong dependence on exhaustible resources constrains the feasibility of sustainable growth. However, since at least some level of production is feasible by relying solely on renewable resources, the sustainable production *level* at a certain moment in time, which depends on the backstop technology, is restricted -- rather than the sustainable growth rate, which depends on the succes and the willingness to invest in technological change that improves the efficiency of (renewable and exhaustible) resource use.[6]

2. Formal models

Formal models that are consistent with the criteria in Table 1 examine further the implications of biophysical constraints and knowledge creation for sustainability and growth. We consider how the concepts developed above can be incorporated in models where the standard (neoclassical) assumptions of individual utility and profit maximizing apply.

Table 2 summarizes the model structures of environmental endogenous growth models that have recently been constructed.[7] The model structure consists typically of three building blocks (cf. Figure 1). The first block is the ecological block, describing how environmental variables are influenced by economic variables and feedback mechanisms. Second, the technology block (production function) models how economic goods are produced by using both natural and man-made inputs. Finally, the preference block (utility function) representing the value system determines the value of natural and man-made goods.

The arrows in Figure 1 represent the many possible interactions between the three blocks. In particular, the environment affects the preference block, because environmental quality has an *amenity* value, so that it enters the utility function. Moreover, the environment exhibits a *productive* value, so that it enters the production function. Also, environmental quality affects the regeneration capacity of the environment and affects life-support systems; a viable economy must therefore keep environmental quality above some critical level. Economic activity affects the environment by using and transforming natural inputs. Pollution and extraction of (renewable) resources involve entropic processes reducing the quality of the environment. Furthermore, economic activity protects renewable resources by allocating energy and material for compensation of entropic processes (*abatement* and *recycling*). At the same time, the development and application of environmentally-friendly technologies reduces future pressure of economic activity on the environment.

2.1. An illustrative model

The smallest model that meets the criteria above specifies a single equation for each building block in the following way (cf. Smulders (1995)):

$\dot{N} = E(N, R_0) - R$	natural resource growth	(1)
$\dot{H} = Y(N, R, H) - C$	knowledge production	(2)
$W = \int_0^\infty U(C, H, N) \exp(-\vartheta t)\, dt$	(intertemporal) utility	(3)

The *a priori* restrictions on (1)-(3) to meet the criteria in Table 1 are (subscripts attached to function symbols denote partial derivatives):

law of entropy:	$E(0, R_0) \leq 0$, $E(N, 0) < 0$, $E_{Ro} > 0$, R_0 given;
essential inputs:	$Y(0,R,H) = Y(N,0,H) = Y(N,R,0) = 0$;
	$U(0,H,N) = U(C,0,N) = -\infty$;
	$Y_N \geq 0$, $Y_R > 0$, $Y_H > 0$, $U_C > 0$, $U_H > 0$, $U_N \geq 0$;
other constraints:	$R \geq 0$, $C \geq 0$, $H \geq 0$, $Y \geq 0$; $N(0)$, $H(0)$ given.

where N is an indicator of nature measured in physical units (natural resources or environmental quality), R_0 is the exogenous free solar-energy inflow, R is the amount of natural resources that is transformed in economic activity (and thus subject to entropy), Y is economic activity (production), H is the stock of (man-made) knowledge, and C is consumption of man-made goods, $U(\cdot)$ is instanteneous utility, ϑ is time preference; all variables depend on the time index t.

In accordance with the law of entropy, eq. (1) shows that new natural inputs (i.e. energy/material, N) can be created only by transforming the external energy flow R_0 into available energy/material N. Natural resources N can be used in production but this use implies transformation and hence entropy: the "extractive" use (i.e. the entropic transformation) of N in economic activity is represented by R, which decreases N. Both extraction of natural resources (where nature N acts as a source) and the disposal of wastes (where N acts as a sink) are captured by R, since both activities diminish the stock of available (low entropy) natural resources.

Without extractive activity (R=0) and with a constant inflow R_0, the dynamics of environmental quality is determined by the natural regeneration processes $E(\cdot)$. The natural regeneration function $E(N,R_0)$ is concave in N (i.e. inverted U-shaped). Hence, the larger the stock of high entropy resources is, the faster entropic processes occur and thus the more difficult it is to compensate entropic processes with the fixed external energy inflow R_0. The natural steady-state equilibrium is the "virgin state", say $\bar{N}(0)$. This resource stock or level of environmental quality is bounded and constant in equilibrium, since the constant external energy inflow R_0 cannot sustain an ever-growing stock of natural resources due to the laws of thermodynamics. If economic activity transforms natural inputs (i.e. if R>0), by harvesting resources and dumping wastes, entropic processes accelerate. Consequently, the virgin-state stock of natural resources can no longer be sustained, since the given energy inflow R_0 is now insufficient to compensate entropic processes. Hence, for a constant extraction rate R, an ecological equilibrium with lower environmental quality results, say $\bar{N}(R)<\bar{N}(0)$.[8]

The technology block is given by eq. (2). Production (Y) is allocated to consumption (C) and investment in new man-made knowledge ($\dot{H}$). Hence, knowledge creation requires investment. The production technology $Y(\cdot)$ uses man-made inputs (H) and natural inputs (R). N enters the production function because a higher environmental quality renders the economy more productive. To illustrate, human health benefits from high environmental quality, which stimulates labor productivity and creativity. This productive aspect of nature is typically *non-rival* and non-extractive in use. For example, one and the same ozone layer protects any individual on earth -- independent of how many individuals have to be protected. Biodiversity conserves genetic information inspiring the search for new products and new applications of natural resources independent of how many researchers study the environment. These aspects of natural resources are thus not depleted by benefiting from them. In other words, no (or only negligible) entropic processes are involved. In contrast, energy and material use (denoted by R) are rival (only one producer can employ the same joule of energy at the same time) and deplete natural resources.

The preference block is modeled by the utility function in (3). Produced consumption and environmental amenities are the arguments of the utility function (cf. Krautkraemer 1985). How much amenity value consumers derive from the physical environment (N) depends on knowledge (H).

The enjoyment of high environmental quality involves non-extractive use of natural resources. This use is non-entropic, since seeing and enjoying a unspoilt environment need not transform it.[9]

2.2. Feasibility and optimality of economic growth

If production, investment and problem-solving yield new ideas and if knowledge spillovers inspire others, diminishing returns may be absent in the creation of knowledge, as argued above. With constant returns in production with respect to the man-made knowledge input, holding fixed other inputs, and a constant fraction of economic activity s_H devoted to knowledge creation, we may write:

$$Y(N, R, H) = y(N, R) \cdot H, \tag{4}$$

$$C = (1-s_H) \cdot Y(.). \tag{5}$$

By substituting $N=\bar{N}(R)$ [from (1) with $\dot{N}=0$], as well as (4) and (5) into (2), we can derive the following expression for the feasible long-run growth rate of knowledge:

$$\dot{H}/H = s_H \cdot y(\bar{N}(R), R). \tag{6}$$

With sustainable rival use of the physical environment (i.e. R constant), the growth rate of knowledge $\dot{H}/H$ is constant and positive. Moreover, the growth rates of consumption (C) and economic activity (Y), both measured in economic terms, are equal to $\dot{H}/H$ and hence constant and positive. At the same time, the level of environmental quality (N), measured in physical units, is constant. Hence knowledge creation fuels economic growth without deteriorating the environment.

If there were diminishing returns with respect to man-made inputs (in casu H), the average productivity of knowledge $Y/H=y(\cdot)$ would diminish over time. Human ingenuity then decreases if man gains knowledge. Thus growth would vanish. Formally, sustained growth is feasible if production exhibits constant returns with respect to reproducible (man-made) factors of production.[10] The latter condition is related to a condition on the elasticity of substitution between man-made reproducible factors and the other inputs in production (σ_Y). If man-made capital (*in casu* knowledge) is a bad substitute for energy ($\sigma_Y<1$), the condition stated is violated: if man-made inputs grow while natural inputs remain constant, the marginal product of capital falls and eventually an additional unit of capital would be worthless. With low substitution possibilities, the maximum amount of production is limited by the scarce factor, so that growth is bounded by natural resources (cf. Dasgupta and Heal 1974). At the same time, natural resource and knowledge inputs are essential (as required by d. in Table 1) only if the substitution elasticity does not exceed unity. Thus sustainable growth requires a unitary elasticity ($\sigma_Y=1$).[11]

The preference block determines the optimal consumption rate $1-s_H$ and extraction rate R and therefore the optimal growth rate, see (6). Whether sustainable consumption levels and extraction rates are optimal (in the sense of maximizing the present value of utility) depends on the specification of the utility function. If the marginal product of investment in man-made inputs is constant in terms of production, but if at the same time the relative price (marginal utility) of produced goods falls relative to that of environmental services, society finds it optimal to shift investment from production towards the environment. Non-growing natural resources become scarcer over time relative to growing produced consumption goods. As a consequence, the optimal allocation of investment is affected in two opposing directions. First, income effects, arising from factor accumulation, increase the demand for environmental goods. Second, substitution effects, arising from the growing relative scarcity of natural goods, divert demand away from environmental goods to produced goods. If both effects cancel, there is an incentive to sustain investment in production growth and preserve a constant physical scale of the environment. If the income effect dominates, however, optimal consumption levels may fall over time whereas optimal investment in the environment increases. Hence, economic growth stops.

2.3. Institutions: private and public man-made goods

The model in (1)-(3) is now extended by introducing the distinction between private and public goods in a decentralized economy, in order to examine public policies to attain sustainability. To this end, rival inputs are separated from non-rival inputs. Man-made inputs such as physical capital equipment and labor are *rival* because a unit employed by one producer cannot be employed at the same time by another. Equivalently, rivalry applies to natural inputs such as energy or other extracted resources and the use of the environment as a sink for wastes. Producers compete for extracted resources. The sink that is filled with pollution of one producer cannot be filled with pollution of another one at the same time. In contrast, other man-made inputs (e.g. knowledge) and natural inputs (e.g. biodiversity and the ozone layer) are *non-rival*, as argued above. Finally, rivalry applies to consumption goods: physical consumption goods are rival but the enjoyment of a clean environment may be non-rival.

The following extended model allows for both the distinction between natural and man-made goods and that between rival and non-rival goods:

$$\dot{N} = E(N, R_0) - \Sigma R_i - R_I \qquad \text{natural resource growth} \qquad (7)$$

$$\Sigma \dot{K}_i + \dot{K}_I = \Sigma Y_i(N, R_i, K_i, H) - \Sigma C_j \qquad \text{rival input production} \qquad (8)$$

$$\begin{cases} H = \kappa \Sigma K_i \qquad (\text{and } R_I = \dot{K}_I = 0) & \text{knowledge} \qquad (9a) \\ \dot{H} = G(N, R_I, K_I, H) & \text{creation} \qquad (9b) \end{cases}$$

$$U_j = U(C_j, H, N) \qquad \text{utility} \qquad (10)$$

Rival inputs are subscripted *i* (and *I*) to denote the representative firm (and the R&D sector) to which the input is allocated. Rival consumption goods are subscripted *j* to denote the consumer. Rival inputs, rival consumption and firms' production (Y_i) can be aggregated as is denoted by the summation sign. There are two man-made inputs: rival capital *K*, including e.g. physical capital and human capital, and non-rival knowledge *H*. There are two natural inputs: *R*, which represents the rival use of the environment[12], and *N*, which is a non-rival input in production and utility.

Equations (9a) and (9b) describe alternative ways to model knowledge creation (see Section 1.3). First, in (9a) knowledge is created as a side-product of investment (this is inspired by Arrow (1962) and Romer (1986) and applied in an environmental context in Michel (1993), and Xepapadeas (1993)). Investment brings about a changing environment with new challenges and problems. Continuous investment efforts must be linked with problem-solving and learning-by-doing. This implies a rise in experience and knowledge. Firms learn not only from own activities but also from problem-solving done by other firms. In this view, the stock of knowledge increases with aggregate investment in the economy.

Second, in (9b) knowledge creation is a separate deliberate activity that takes the form of research and development or education. Resources are purposefully allocated to knowledge-generating activities. The R&D activities yield product designs that can be patented and sold to firms to cover the cost of the patent out of monopoly profits (cf. Grossman and Helpman (1991), applied in an environmental context by Verdier (1993) and Hung et al. (1993)). In the absence of a patent market, an incentive for private research activities also exists if it yields firm-specific knowledge that is difficult to copy by other firms (i.e. tacit knowledge, see Smulders and Van de Klundert (1995)). If, however, researchers are not able to appropiate the fruits from their work, e.g. when all firms operate in a perfectly competitive market so that the fixed cost of research cannot be paid for, the government should provide (or fully subsidize) new knowledge (Bovenberg and Smulders (1993, 1994)).

Sustainable growth is feasible if the marginal productivity of man-made inputs remains bounded away from zero if man-made inputs become abundant relative to aggregate resource use $R \equiv \sum R_i + R_I$ and environmental quality N. This restricts the technology for production and that for knowledge creation.[13] A sufficient condition is constant returns with respect to the man-made inputs K and H taken together in both $Y_i(\cdot)$ and $G(\cdot)$, as e.g. in the following specification:

$$Y_i(\cdot) = \alpha_Y(N) \cdot F(K_i, HR_i) \tag{11}$$

$$G(\cdot) = \alpha_G(N) \cdot f(K_I, HR_I) \tag{12}$$

where $F(\cdot)$ and $f(\cdot)$ are linear homogenous in the two arguments. The knowledge variable H can be interpreted as natural-resource-augmenting, energy-augmenting or pollution-augmenting technologies (in analogy to labor-augmenting technological progress); it is knowledge that directly increases the productivity of natural resources (e.g. 2 and 3 in Table 2). HR measures the "effective resource input", i.e. it transfroms the physical dimension of R into an economic dimension that indicates how valuable resources are in value creation. Energy-augmenting knowledge substitutes for energy within effective inputs with unitary elasticity, which implies that the marginal productivity of new technologies (H) does not diminish if resource inputs remain constant. To satisfy condition d in Table 1, substitution between K and HR in $f(\cdot)$ and $F(\cdot)$ is at most unity; constant returns with respect to private capital K_i and resource inputs measured in efficiency units together form a sufficient condition for the feasibility of endogenous growth. Others (see row 1, 8, 9 in Table 2) include the non-rival man-made input separately in $Y(\cdot)$ and interpret it as infrastructure (cf Barro 1990).

2.4. Pollution and abatement

Many environmental growth models focus not on environmental quality and resource extraction, but on environmental damage and pollution (see row 3, 5-8, 10-15 in Table 2). However, as long as the environment is modeled as a one-dimensional variable, the laws of thermodynamics suggest that the two approaches are related to each other. Environmental damage is no more than physical disorder, i.e. the result of the transformation of low entropy into high entropy. Environmental quality N represents the stock of low-entropy resources. The stock of pollution, to be denoted by S, is the stock of high-entropy resources. Entropic extraction activities R reduce the stock of low entropy resources and increase the stock of high-entropy resources. By the law of conservation of material/energy, no resources are lost in this process. Hence, the actual stocks of high and low entropy sum to a constant, say $\bar{E}$, so that the stock of wastes (S) and environmental quality (N) are linked as follows:

$$S = \bar{E} - N \tag{13}$$

Eliminate N between (1) and (13) to find the change in the stock of pollution:

$$\dot{S} = R - \delta(S, R_0) \tag{14}$$

where $\delta(S, R_0) = \delta(\bar{E} - N, R_0) \equiv E(N, R_0)$. The term $\delta(S, R_0)$ in (14) represents the absorption capacity of the environment: using solar energy, eco-systems are able to assimilate wastes, i.e. to transform unavailable energy (pollution) into available energy (natural resources). It has been argued above that $E(N,R_0)$ is concave in N, which implies that $\delta(S,R_0)$ is also concave in S (cf. Cesar (1994), Pethig (1994)). This contrasts with the often applied assumption that the ecosystem assimilates a constant proportion (δ_S) of the waste stock, i.e. $\delta(S, R_0) = \delta_S \cdot S$ (e.g. Van der Ploeg and Withagen (1991), see also row 3, 10-13, 15 in Table 2).

Natural resource use R in (14) can be interpreted as the rival use of the environment as a sink, i.e. the flow of pollution that adds to the stock S. Hence, the input R in production [see $Y(\cdot)$ in (2)] is a polluting input, or pollution is a side-product of this particular input (Table 2 denotes pollution by P, so that $R=P$, see row 1, 2, 12). Substitution between pollution (polluting inputs) and other inputs is specified by the production function.

An alternative way to model the economy-environment interaction is to focus on pollution as an inevitable side-product of economic activity, rather than of a particular input. In this approach, the flow of pollution is a joint product of economic activity, i.e. pollution is directly related to total production (Y) (see 7, 11, 14 in Table 2; cf. Keeler, Spence and Zeckhauser (1971)). Since the flow of pollution involves resource extraction (R), this approach is equivalent to the assumption of a fixed natural-resource input coefficient. Substitution possibilities are introduced in this approach by assuming that pollution can be abated by giving up some part of production (see 3-6, 8-10, 13, 15 in Table 2, cf. Forster (1973)).

An illustration of the latter specification with pollution as a side-product and abatement is given by the following equations:

$$\dot{S} = \Sigma R_i - \delta(S, R_0) \tag{15}$$
$$\Sigma \dot{K}_i = \Sigma Y_i(S, K_i, H) - \Sigma C_j - \Sigma A_i - A_I \tag{16}$$
$$R_i = P_i(Y_i, A_i, A_I) \tag{17}$$
$$H = \kappa \Sigma K_i \tag{9a}$$
$$U = U(C_j, H, S) \tag{18}$$

The firm's pollution emission (or more general natural resource use, R_i) depends positively on the firm's production Y_i, and negatively on private abatement A_i and public abatement A_I, see (17). Note that I formulated the environmental variable as pollution rather than environmental quality (S instead of N) by using (13), so that $\partial Y_i/\partial S<0$, $\partial U_j/\partial S<0$. Abatement services are modeled as a flow and are produced according to the same technology as physical capital and consumption goods, see (16). In alternative specifications, abatement is either private (e.g. Bovenberg and de Mooij (1994)) or public (e.g. Michel (1993)), public abatement is treated as a stock variable (e.g. Xepapadeas (1993)), abatement is produced according to a separate technology (e.g. Michel (1993)), or the flow of pollution enters the utility function. Instead of (9a), knowledge may be purposefully produced, e.g. as in (9b).

Growth is sustainable only if abatement has a knowledge dimension. If abatement consisted of private cleaning devices (e.g. scrubbers) with given productivity, a doubling of all rival inputs (K_i and A_i) would result in a doubling of output and pollution (Y_i and P_i) by the standard replication argument (intuitively, you just build another of the same factory, see Romer 1990b). Hence, a balanced growth path (where $\dot{A}/A=\dot{K}/K$) would be unsustainable since the physical dimension of pollution grew. However, increases in the productivity of abatement, i.e. in the knowledge dimension of abatement, allow for growth in production with constant pollution without the need to increase the fraction of output devoted to abatement (A/Y). In this respect, the abatement variable in (16)-(17) is similar to the knowledge that increases the productivity of polluting inputs in (8). It would be conceptually clearer to separate the quantity dimension of abatement, (measured in rival units) and its quality dimension (i.e. its productivity or the (non-rival) knowledge embodied in abatement goods), as e.g. in the following equations which may replace and specify (16)-(17):

$$\Sigma Y_i = \Sigma \alpha_Y(S) \cdot K_i^{\beta} \cdot (H^{\alpha} L_i)^{1-\beta} = \Sigma \dot{K}_i + \Sigma C_j + \Sigma A_i \tag{19}$$
$$R_i = Y_i^{1+\gamma} \cdot (H_A{}^{\eta} A_i)^{-\gamma} \tag{20}$$
$$\dot{H}_A = \Sigma A_i \tag{21}$$

where L_i is a rival fixed factor (e.g. space or land). Accordingly, production and resource use are homogeneous of degree one in rival factors, holding fixed other factors, to satisfy the replication argument (cf. Chung-Huang and Deqin (1994)). Productivity improvements in abatement technology, denoted by $\dot{H}_A$, arise as a side-effect of scrubber production, *cf.* learning by doing (van Ewijk and van Wijnbergen (1995) analyze purposeful improvements in abatement technology). The specifications of the production function and pollution function determine the feasibility of sustained balanced growth. It can be checked that in (19) and (20) balanced growth with constant A/Y, C/Y and R is feasible if $\alpha=1$ and $\eta=1/\gamma$. More flexible forms, notably specifications that include adjustment costs in capital production, allow for less strict conditions (cf. Romer 1986).

3. Conclusions and some implications for public finance

Knowledge can be viewed as the basic human factor that interacts in economic processes with the basic natural factors: energy and material. Although increases in natural factors are constrained by the fixed influx of solar energy, human ingenuity may increase knowledge. Endogenous growth theory stresses the properties of knowledge. The use of knowledge is unlimited and without opportunity cost because of its non-rival nature. Moreover, the accumulation of knowledge can be based on existing knowledge: old knowledge inspires new knowledge. This fuels economic growth by offsetting diminishing returns and ecological limits in creating economic value.

The first important aim of this paper is to show how new knowledge creation makes it possible to reconcile economic growth with environmental preservation. The formal models surveyed here reveal formal conditions for the feasibility of sustainable growth. Two remarks are important for the assessment of these conditions. First, the feasibility conditions obviously depend on the exact specification of the models, which are typically rather simple. Hence, it is no wonder that the conditions for sustainability are stylized and often very stringent (e.g. with respect to returns to scale, substitution elasticities in production, preference structures, etc.). More complex or realistic basic assumptions regarding production structure, adjustment costs, etc, may lead to less stringent conditions under which sustainable growth is feasible. Second, whatever the exact nature of the formal condition, the basic interpretation is that if human ingenuity is large enough, limits from nature can be offset. Ingenuity should be interpreted broadly as encompassing also inventions, innovations and developments that change institutional settings, substitution possibilities, and preferences.

A second message of endogenous growth theory is that growth requires investment. Pure market mechanisms often yield suboptimal levels of investment due to the non-rival nature of growth-sustaining inputs (knowledge, infrastructure, etc.). Without appropriate intervention, consumption and investment patterns may damage the environment. Hence, sustainable growth requires environmental policies that guarantee sufficient levels and the right direction of investment, especially in resource conservation, abatement, and the development of pollution-saving technologies.

Apart from indicating policies to reach sustainable growth, the formal models surveyed examine how *changes* in environmental policy influence growth, given that the policies are sufficient to guarantee sustainability. In general, two opposing effects may arise. On the one hand, increases in abatement and environmental R&D activities may crowd out other investment, which tends to harm growth. On the other hand, a tightening of environmental policy improves environmental quality so that the economy benefits from more non-rival (and rival) services from nature. This boosts economic productivity and increases the incentive for investment and growth. Indeed, if the latter effect dominates, a double dividend arises, i.e. environmental policy improves both the environment and economic growth.

Many issues still remain to be investigated in formal models. Irreversibilities and ecological threshold effects ("critical loads"), which are likely to have substantial impacts on the link between environment and growth, are too often neglected. The function of the environment as a life-support system is modeled neither explicitly nor independently of its role in production or utility. Transitional effects of environmental policy are often ignored, either by restricting the analysis to models without transition dynamics or by focusing exclusively on the steady state results (exceptions are Bovenberg and Smulders (1994), Van Ewijk and Van Wijnbergen (1994)).

Most models fail to explain a number of important *stylized facts* on growth and the environment in the real world. First, exhaustible parts of the environment are the main source for energy and materials in current production technologies. The distinction between resources that are renewable and resources that are exhaustible on a human time scale as well as the transition to more durable resources deserve more attention. A desaggregation of the environmental variable is useful (cf. Tahvonen and Kuuluvainen (1993)). Second, population pressure is one of the most important sources of environmental degradation. At the same time, life expectancy and health depend on environmental quality. This requires a proper modeling of population growth. A third stylized fact regards the correlation between the level of income and pollution. Low and high levels of income are associated with relatively low pollution, but pollution is high at medium-income levels (e.g. World Development Report 1992). Environmental endogenous growth models are silent about these kinds of correlation (an exception is Van Ewijk and Van Wijnbergen (1994); Xepapadeas (1993) considers low-development traps). Fourth, prices of natural resources decline over time, while most models predict increasing prices. Fifth, innovation may *in*crease physical resource use and environmental problems. Most models focus on resource-saving technological progress only, and thus fail to deal with the direction (or "bias") of technological progress. Sixth, the interaction between public policies and private firms' activities in creating new (environmentally friendly) technologies and in undertaking private abatement activities is much more important than suggested by the current models. By incorporating firm-specific knowledge, in-house R&D, imperfect competition, and cooperative action, much can be gained.

Even without taking full account of all these refinements, the endogenous growth framework set out in this paper provides a useful starting point for studying more complex and explicit policy issues. Realistic (second-best) policy rules and other aspects of public finance are already (though scarcely) incorporated by some authors (see Bovenberg and De Mooij (1994), Ligthart and Van de Ploeg (1994) and Sørensen, Pedersen and Nielsen (1994)). Further issues concern the choice of instruments, how to cope with information asymmetries and uncertainty, and implications of political economy. The challenge is to find and implement environmental and economic policies that stimulate society's ingenuity and that employ it in the right direction in order to achieve sustainable development.

Notes

1. Problems arise in defining economic growth. It would be ideal to be able to measure the (direct and indirect) contribution of economic activities to utility. However, utility is not measurable. Since we use prices, GNP values against *marginal* utility. Moreover, GNP excludes the indirect effects of economic activity that occur outside the price system: e.g. activities within the informal economy and externalities are not counted. To come closer to the ideal index, we should not include the part of national production that serves not to satisfy wants but only to restore adverse consequences of economic activity, such as capital depreciation expenditures and defensive expenditures like industrial pollution abatement. As shown by Hartwick (1990), the resulting Net National Product is a correct index for utility -- provided that all market prices equal the shadow prices (i.e. all externalities are internalized).

2. In economics, technology and preferences are traditionally given and technological change is represented by shifts in the parameters of the production function. Models of induced technological progress and endogenous growth endogenize these shifts. Basically the "shift parameter" becomes an variable input (labeled knowledge) in a "meta"-production-function. This removes the artificial distinction between shifts of and movements along the production function. Analoguously, a meta-preference-function that includes knowledge can be formulated.

3. The work by Daly is often misunderstood and interpreted as a rejection of the feasibility of long-run economic growth. See Daly's (1980) Postscript for a clarification on economic growth within his concept of a "steady-state" economy. Daly defines growth as quantitative increase in the scale of the economy, which must ultimately stop. This paper applies a more conventional definition (*viz.* value growth) which also includes changes in product quality, shift to services, etc. Daly uses the term development for qualitative change. This may be misleading, since it is hard to imagine growth without qualitative change (cf. Scott 1989).

4. Note that in this representation matter/energy and knowledge are the primary production factors, i.e. knowledge is something distinct from the (material) medium on which it is stored (Romer 1990b, p. 97). (Physical) capital and labor (human capital) are *derived* production factors.

5. Creative destruction may degradate particular ideas (e.g. Aghion and Howitt 1992), but only through replacing them by more useful ideas so that the total knowledge stock increases.

6. Aalbers (1995) considers physically sustainable growth paths in an economy (without technological progress) in which natural resources are partly renewable, partly exhaustible.

7. Not all models summarized satisfy the criteria in Table 1. In Van Marrewijk et. al. (1993) environmental quality grows forever at a constant rate in the steady state. This violates the law of entropy. In Hung et. al. (1993) and Ligthart and Van der Ploeg (1994), pollution grows in the steady state. This must destroy eventually the environment and is therefore unsustainable.
Some papers (see 5-8, 14 in Table 2) consider the environment only as a flow. For steady-state analysis this may be justified (see Smulders and Gradus 1993). It simplifies the analysis considerably and makes it possible to derive closed-form solutions e.g. if the tax-structure is complicated.

8. Irreversibilities can be modeled by replacing (1) by $\dot{N} = -max\{R - R_{cl}, 0\}$ where R_{cl} is the critical load that can be absorbed by the environment without environmental damage (cf. Aalbers (1995)).

9. The model can easily be extended for rival "consumption" of amenities, to capture e.g. adverse effects of tourism. Note, however, that tourism services are produced and marketed so that tourism is incorporated already in $Y(.)$ and C.

10. See Rebelo (1991, p.502): "All that is required to assure the feasibility of perpetual growth is the existence of a 'core' of capital goods that is produced with constant-returns technologies and without the direct or indirect use of non-reproducible factors." Sala-i-Martin and Mulligan (1993) show that if the core consists of two capital goods, decreasing returns in the technology to produce one of them have to be offset by increasing returns in the technology to produce the other one. Bovenberg and Smulders (1993) show that fixed (non-reproducible) factors may play a role in the technologies of the core, provided that the elasticity of substitution between the fixed factors and the (sub)set of core capital goods is unity.

11. Models with more sectors and more inputs generate less stringent conditions on substitution elasticities, see following sections.

12. Labor is part of R_i with respect to its physical aspect (labor services represent energy and need nature N to be regenerated), and is included in K_i with respect to its human capital (labor has a knowledge dimension, which is the (man-made) ability to create value).

13. Rebelo's (1991) core property applies, see footnote 10.

References

Aalbers, R.B.T. 1995, `Extinction of the Human Race: Doom-Mongering or Reality?' forthcoming in *De Economist* 143, No. 2.

Aghion, Ph. and P. Howitt 1992, `A Model of Growth through Creative Destruction', *Econometrica* 60, pp. 323-352.

Arrow, K. 1962, `The Economic Implications of Learning by Doing', *Economic Inquiry*, 28, pp. 1-18.

Barro, R.J. 1990, `Government Spending in a Simple Model of Endogenous Growth', *Journal of Political Economy*, 98, s103-s125.

Bovenberg, A.L. and R.A. de Mooij 1994, `Environmental Tax Reform and Endogenous Growth', *CentER Discussion Paper* 9498, Tilburg University.

Bovenberg, A.L. and S. Smulders 1993, `Environmental Quality and Pollution-augmenting Technological Change in a Two-sector Endogenous Growth Model', *CentER Discussion Paper* 9321, Tilburg University, forthcoming in *Journal of Public Economics*.

Bovenberg, A.L. and S. Smulders 1994, `Transitional Impacts of Environmental Policy in an Endogenous Growth Model', *CentER Discussion Paper* 9450, Tilburg University.

Boulding, K.E. 1966, 'The economics of the coming spaceship Earth', in H. Jarrett (ed.), *Environmental Quality in a Growing Economy*, John Hopkins University Press, Baltimore.

Butter, F.A.G. den, and M.W. Hofkes 1993, `Sustainable Development with Extractive and Non-extractive use of the Environment in Production', *Research Memorandum* 1993-55, Free University Amsterdam.

Cesar, H.S.J. 1994, *Control and Game Models of the Greenhouse Effect; Economics Essays on the Comedy and Tragedy of the Commons*, Lecture Notes in Economics and Mathematical Systems 416, Springer-Verlag, Berlin.

Chung-huang Huang and Deqin Cai 1994, 'Constant Returns Endogenous Growth with Pollution Control', *Environmental and Resource Economics* 4, pp. 383-400.

Daly, H.E. (ed.) 1973, *Towards a Steady-State Economy*.

Daly, H.E. 1980, `Postscript: Some Common Misunderstandings and Further Issues Concerning a Steady-State Economy', in: H.E. Daly (ed.) *Economics, Ecology, Ethics; essays towards a steady-state economy*, W.H. Freeman & Co., San Francisco; reprinted in Daly (1993).

Daly, H.E. 1987, 'The Economic Growth Debate: what some economists have learned but many have not', *Journal of Environmental Economics and Mangement* Dec. 1987, reprinted in A. Markandya and J. Richardson (eds.) *The Earthscan reader in Environmental Economics*, London 1992.

Daly, H.E. 1992, `Comment: Is the Entropy Law Relevant to the Economics of Natural Resource Scarcity?-Yes, of Course It Is!', *Journal of Environmental Economics and Management* 23, pp. 91-95.

Daly, H.E. and K.N. Townsend (ed.) 1993, *Valuing the Earth; Economics, Ecology, Ethics*, MIT Press, Cambridge MA.

Dasgupta, P. and G. Heal 1974, 'The Optimal Depletion of Exhaustible Resources', Review of Economic Studies, pp. 3-28.

Ewijk, C. van, and S. van Wijnbergen 1994, 'Environmental Policy and Economic Growth', mimeo, university of Amsterdam, fortcoming *CEPR Discussion Paper*.

Ewijk, C. van, and S. van Wijnbergen 1995, `Can Abatement Overcome the Conflict between Environment and Economic Growth?', forthcoming in *De Economist* 143, No. 2.

Forster, B.A. 1973, `Optimal Capital Accumulation in a Polluted Environment', *Southern Economic Journal*, 39, pp. 544-547.

Georgescu-Roegen, N. 1971, *The entropy Law and the Economic Process*, Harvard University Press.

Georgescu-Roegen, N. 1975, `Energy and Economic Myths', *Southern Economic Journal* 41, pp. 347-381.

Gradus, R. and S. Smulders 1993, `The Trade-off between Environmental Care and Longterm Growth; pollution in three proto-type growth models', *Journal of Economics* 58, pp. 25-51.

Grossman, G.M. and E. Helpman 1991, *Innovation and Growth in the Global Economy*, MIT Press, Cambridge MA.

Hartwick, J. 1990, `Natural Resources, National Accounting and Economic Depreciation', *Journal of Public Economics* 43, pp. 291-304.

Hung, V.T.Y., P. Chang and K. Blackburn 1993, `Endogenous Growth, Environment and R. and D.', Fondazione ENI Enrico Mattei, Nota di Lavoro 23.93.

Keeler, E., M. Spence and R. Zeckhauser (1971), 'The Optimal Control of Pollution', *Journal of Economic Theory* 4, pp. 19-34.

Kneese, A.V., R.U. Ayres, R.C. d'Arge 1970, *Economics and the Environment, A Material Balance Approach*, Resources for the Future, The Johns Hopkins Press, Baltimore.

Krautkraemer, J. A. 1985 `Optimal growth, Resource Amenities and the Preservation of Natural Environments', *Review of Economic Studies* 52, pp. 153-170.

Ligthart, J.E. and F. van der Ploeg 1994, `Pollution, the Cost of Public Funds and Endogenous Growth', *Economic Letters* 46, pp. 351-361.

Marrewijk, C. van, F. van der Ploeg and J. Verbeek 1993, `Pollution, Abatement and Endogenous Growth: Is Growth bad for the Environment?', Working Paper, World Bank, Washington.

Michel, Ph. and G. Rotillon 1992, `Pollution's Disutility and Endogenous Growth, mimeo, Université de Paris I.

Michel, Ph. 1993, `Pollution and Growth towards the Ecological Paradise', *Fondazione Eni Enrico Mattei* Working Paper 80.93.

Mishan, E.J. 1993, *The costs of Economic Growth* (new edition), Weidenfeld and Nicolson, London (original edition 1967).

Mulligan, C. and X. Sala-i-Martin 1993, `Transitional Dynamics in Two-sector Models of Endogenous Growth', *Quarterly Journal of Economics*, 108, nr. 3, pp. 739-773.

Musu, I. 1995 'Transitional Dynamics to Sustainable Growth', mimeo, University of Venice.

Neumann, J. von 1938, `Über ein Ökonomisches Gleichungssystem und eine Verallgemeinerung des Brouwerschen Fixpunktsatzes', in: Ergebnisse eines Mathematischen Seminars, Wien, translated in *Review of Economic Studies*, 13, 33, pp. 1445-46.

Perrings, C. 1987, *Economy and Environment; A Theoretical Essay on the Interdependence of Economic and Environmental Systems*, Cambridge University Press, Cambridge.

Pethig, R. 1994 `Ecological Dynamics and the valuation of environmental change', mimeo.

Pezzey, J. 1992, `Sustainability: an Interdisciplinary Guide', *Environmental Values* 1, pp. 321-362.

Ploeg, F. van der, and C. Withagen 1991, `Pollution control and the Ramsey Problem', *Environmental and Resource Economics* 1, 215-230.

Rebelo, S. 1991, `Long-run Policy Analysis and Long-run Growth', *Journal of Political Economy* 99, 500-521.

Romer, P.M. 1986, `Increasing Returns and Long-run Growth', *Journal of Political Economy* 94, 1002-1037.

Romer, P.M. 1990a, `Endogenous Technological Change', *Journal of Political Economy*, 98, pp. s71-s102.

Romer, P.M. 1990b, `Are Nonconvexities important for Understanding Growth?', *American Economic Review* 80, AEA papers and proceedings, pp. 97-103.

Romer, P.M. 1994, 'New goods, old theory, and the welfare costs of trade restrictions', *Journal of Development Economics* 43, pp. 5-38.

Scott, M.F. 1989, *A New View of Economic Growth,* Clarendon Press, Oxford.

Smulders, J. 1995, `Environmental Policy and Sustainable Economic Growth; an Endogenous Growth Perspective' forthcoming in *De Economist* 143, No. 2.

Smulders, J. and R. Gradus 1993, `Pollution Abatement and Long-term Growth', *CentER Discussion Paper* 9373, Tilburg University.

Smulders, J. and Th. van de Klundert 1995, `Imperfect Competition, Concentration and Growth with Firm-specific R&D', *European Economic Review* 39, pp. 139-160.

Sørensen, P.B., L.H. Pedersen and S.B. Nielsen 1994, `Taxation, Pollution, Unemployment and Growth: Could there be a "Triple Dividend" from a Green Tax Reform', EPRU Working Paper 1994-10, Copenhagen Business School.

Stiglitz J.E. 1974, 'Growth with Exhaustible Natural Resources: Efficient and Optimal Growth Paths', *Review of Economic Studies* pp. 123-137.

Stiglitz, J.E. 1987, `Learning to Learn, Localized Learning and Technological Progress', in: Dasgupta & Stoneman (eds.), *Economic Policy and Technological Performance*, Cambridge University Press, pp. 125-153.

Tahvonen, O. and J. Kuuluvainen 1993, `Economic growth, Pollution, and Renewable Resources', *Journal of Environmental Economics and Management* 24, pp. 101-118.
Verdier, T. 1993, 'Environmental Pollution and Endogenous Growth: a Comparison between Emission Taxes and Technological Standards', *Foundatione Eni Enrico Mattei* Working Paper 57.93.
World Development Report 1992, The World Bank, Washington.
Xepapadeas, A. 1993, `Long-run Growth, Environmental Pollution and Increasing Returns', mimeo 1993, University of Crete.
Young, J.T. 1991, `Is the Entropy Law Relevant to the Economics of Natural Resource Scarcity?', *Journal of Environmental Economics and Management* 21, pp. 169-179.

Figure 1 Conceptual framework

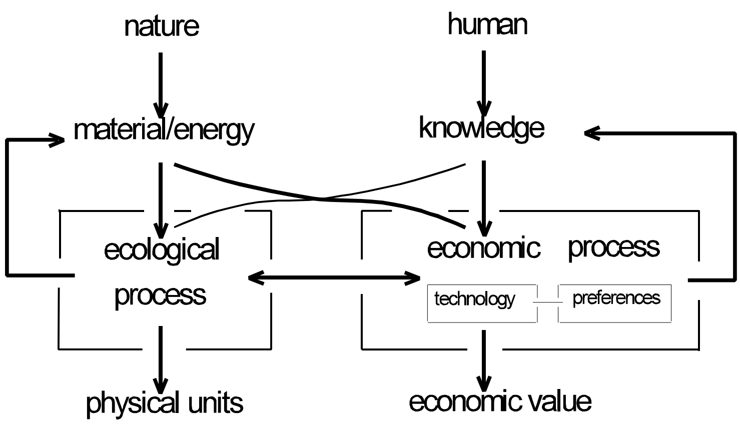

Table 2 Environmental endogenous growth models

	Environment		Technology		Utility
	as a stock	as a flow	production functions	goods market	
1. Bovenberg & de Mooij (1994)	-	$N_{fl} = e(R)$	$Y_i = \alpha_Y(N_{fl}) \cdot F(A_i,K_i,I_g,R_i,L_i)$	$Y = \dot{K} + C + A + I_g + C_g$	$U(C_j,N_{flow},C_g)$ $=[f(C_j,C_g)\cdot N_{fl}]^{1-\rho}/(1-\rho)$
2. Bovenberg & Smulders (1995)	$\dot{N} = E(N,R)$	$P=R=\sum R_{Yi}+R_H$	$Y_i = \alpha_Y(N) \cdot F(K_{Yi},HR_{Yi})$ $\dot{H} = \alpha_H(N) \cdot f(K_H,HR_H)$	$Y = \dot{K} + C$	$U(C_j,N)$ $= (C_j \cdot N^{\phi})^{1-\rho}/(1-\rho)$
3. Chung-Huang & Deqin (1994)	$\dot{S} = P - \delta S$	$P = P(A_i, K_i, A_I)$	$Y_i = \alpha K_i$	$Y = \dot{K} + C + A + A_I$	$U(C_j,S)$ $= (C_j \cdot S^{-\phi})^{1-\rho}/(1-\rho)$
4. den Butter & Hofkes (1995)	$\dot{N} = E(N,P)$	$P = P(R,A)$	$Y = \alpha(N) \cdot F(K,R)$	$Y = \dot{K} + C + A$	$U(C_j,N) = ln(C_j \cdot N^{\phi})$
5. van Ewijk & v Wijnbergen (1994)	-	$P = P(A/K)$	$Y_i = K_i^{\beta} \cdot [\psi(P)H_i L_{Yi}]^{1-\beta}$ $\dot{H}_j = G(P) \cdot H_j \cdot (L - \sum L_{Yi})/L$	$Y = \dot{K} + C + A$	$U(C_j)=C_j^{1-\rho}$
6. Gradus & Smulders (1993)	-	$P = P(A/K)$	$Y = \alpha K$	$Y = \dot{K} + C + A$	$U(C_j,P)$
	-	$P = P(A/K)$	$Y = K^{\beta} \cdot (HL_Y)^{1-\beta}$ $\dot{H} = G(P) \cdot H \cdot (L-L_Y)/L$	$Y = \dot{K} + C + A$	$U(C_j,P)$
7. Hung, Chang & Blackburn (1993)	-	$P = P(X_d)$	$Y = (n_c X_c^{\beta} + n_d X_d^{\beta}) \cdot L_Y^{1-\beta}$ $\dot{n}_s = G(H_s,L_s), \quad s=c,d$ $H_s = n_s$	$Y = C + n_c X_c/\gamma_c + n_d X_d/\gamma_d$	$U(C_j,P) = ln(C_j \cdot P^{-\phi})$
8. Ligthart & V.d. Ploeg (1994)	-	$P = \pi(A/Y) \cdot Y$	$Y_i = K_i^{\beta} \cdot I_g^{1-\beta}$	$Y = \dot{K} + C + C_g + A + I_g$	$U(C_j,P,C_g)$
9. V. Marrewijk et al. (1993)	$[\dot{N} = n(A_1/Y) \cdot N]$	$N_{flow} = e(Y/A_2)$	$Y_i = K_i^{\beta} \cdot I_g^{1-\beta}$	$Y = \dot{K} + C + A_1 + A_2 + I_g$	$U(C_j,N,N_{flow})$

10. Michel (1993)	$\Delta S = P - \delta S_{-1} - A$	$P = R$	$Y_i = \alpha(S) \cdot F(K_{Yi}, HL_i, R_i)$ $A = G(K_A, H, L_A)$ $H = K = K_A + K_Y$	$Y = \dot{K} + C + \gamma R$	$U(C_j, S)$
11. Michel & Rotillon (1992)	$\dot{S} = P - \delta \cdot S$	$P = \pi Y$	$Y_i = F(K_i, HL_i)$ $H = K$	$Y = \dot{K} + C$	$U(C_j, S)$
12. Musu (1995)	$\dot{N} = \delta(\bar{E} - N) - R$	$P = \sum R_i$	$Y_i = K_i^{\beta} \cdot (HR_i)^{1-\beta}$ $H = K$	$Y = \dot{K} + C$	$U(C_j, N)$ $= (C_j \cdot N)^{1-\rho}/(1-\rho)$
13. Smulders & Gradus (1993)	-	$P = P_i = P(A_i, K_i)$	$Y_i = Y(K_i, P_i, P)$ if $P < \bar{P}$ $Y_i = 0$ if $P > \bar{P}$	$Y = \dot{K} + C + A$	$U(C_j, P)$ $= (C_j \cdot P^{-\phi})^{1-\rho}/(1-\rho)$
	$\dot{S} = P - \delta \cdot S$	$P = P(A, K)$	$Y = Y(K, S)$	$Y = \dot{K} + C + A$	$U(C_j, S)$ $= (C_j \cdot S^{-\phi})^{1-\rho}/(1-\rho)$
14. Verdier (1993)	-	$P = \pi \cdot n \cdot X_d$	$C = n^{1/\zeta} X_d$, $X_d = L_x / n$ $\dot{n} = \dot{H} = \alpha(\pi) \cdot H \cdot (L - L_x)$		$U(C, P)$
15. Xepapadeas (1994)	$\dot{S} = P - \delta \cdot S$	$P = \pi(A) \cdot Y$	$Y = F(K_Y, H_Y)$ $A = G(K_A, H_A)$ $H_s = K_s \quad s = A, Y$	$Y = \dot{K} + C$	$U(C, S) = U(C) - D(S)$

Key: A=$\sum A_i$ (A_l) (public) abatement; C=$\sum C_j$ (C_g) (public) consumption; $F(\cdot)$, $f(\cdot)$ a linear homogenous function; H knowledge; I_g infrastructural services; K=$\sum K_i$ capital; L labour or fixed factor; N (N_{fl}) (flow of) environmental quality; n (n_s) number of product variants (of type s); P pollution flow; R extracted resources; S pollution stock; X_c (X_d) clean (dirty) goods; Y production; γ extraction cost; ρ constant rate of relative risk aversion; π pollution output ratio.

List of symbols

A abatement

C (C_g) (public) consumption

$F(\cdot)$, $f(\cdot)$ a linear homogenous function

H knowledge

I_g infrastructural services

K capital

L labour or fixed factor

N (N_{fl}) (flow of) environmental quality

n (n_s) number of product variants (of type s).

P pollution flow

R extracted resources

S pollution stock

X_c (X_d) clean (dirty) goods

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